# ASSESSMENT OF THE ACCURACY OF CERTAIN REDUCED ORDER MODELS USED IN THE PREDICTION OF OCCUPANT INJURY DURING UNDER-BODY BLAST EVENTS


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**-It is a well known fact that underbody blasts have become one of the most widespread reasons for warfighter casualties in recent wars. -Spinal injuries to occupants have particularly increased in theater from these roadside blast incidents, followed by tibia and lower leg injuries. -The most common occupant injuries in these extremely short duration events arise out of the very high vertical acceleration of vehicle due to its close proximity to hot high pressure gases from the blast. -It is of considerable interest to developers of military vehicles to assess occupant injury risk due to blast loading in the early phase of the design process.**

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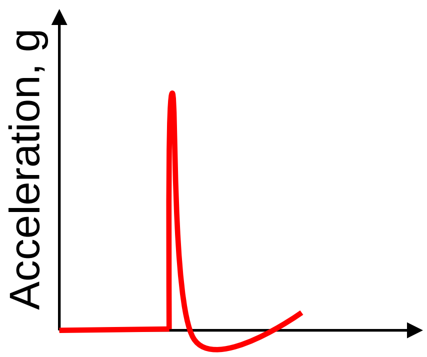
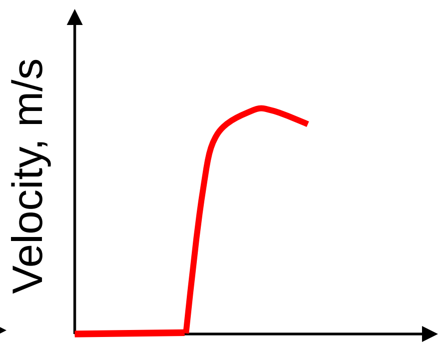
# Introduction

- **It is a well known fact that underbody blasts have become one of the most widespread reasons for warfighter casualties in recent wars.**
- **Spinal injuries to occupants have particularly increased in theater from these roadside blast incidents, followed by tibia and lower leg injuries.**
- **The most common occupant injuries in these extremely short duration events arise out of the very high vertical acceleration of vehicle due to its close proximity to hot high pressure gases from the blast.**
- **It is of considerable interest to developers of military vehicles to assess occupant injury risk due to blast loading in the early phase of the design process.**

## Blast pulse and occupant Injury

A typical blast loading pulse is triangular in shape and can be characterized by its peak acceleration ($G_{peak}$) or change in velocity ($\Delta v$) with or without considering the duration of the pulse ($T$).




Occupant injury risk is proportional to;

1. Peak acceleration, $G_{peak}$ in g's
2. Time duration of the pulse, $T$ in ms
3. Rate of onset of acceleration, $\dot{G}$ in g/ms
4. Change in velocity, $\Delta v$, in m/s
5. Direction of loading
6. etc.

It has been shown before that there is no single input parameter which can be used to effectively assess occupant injury. However, the design community often use peak acceleration, $G_{peak}$ or $\Delta v$ to determine the severity of any given pulse.

Earlier efforts to more adequately characterize the blast loading pulses include defining dependent variables such as Effective-g (slope of the velocity profile), and Specific Power ($G_{peak}$ x $\Delta v$) with some success when compared against a few of the injury criteria.

# Objectives

1. **To determine If a single blast loading parameter is sufficient to adequately identify the occupant injury for the *duration of typical blast events (0-20ms).***

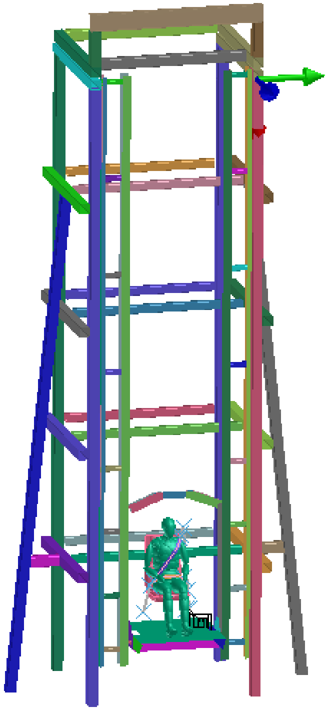
2. **To create look-up tables/response surfaces/automated software tools for the different injury responses by performing a parametric study**

    - for both stroking and non-stroking seat systems.

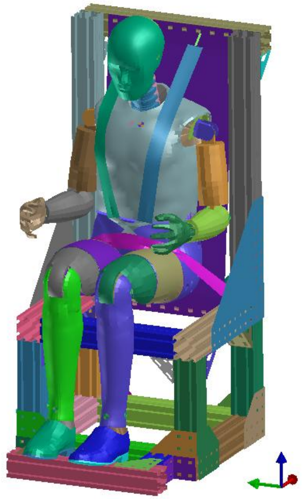
3. **Quantitatively evaluate the accuracy of using such tools in lieu of building a detailed model for simulation and occupant injury assessment.**

# Vertical drop tower test and simulation

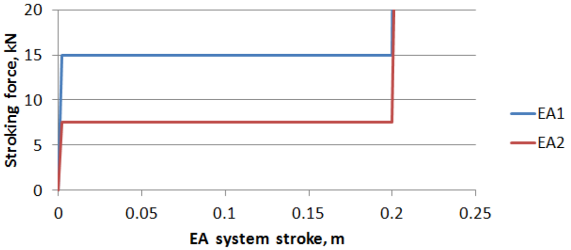
Vertical drop tower test fixture



MADYMO Dynamic simulation model including Q-version of Hybrid III ATD



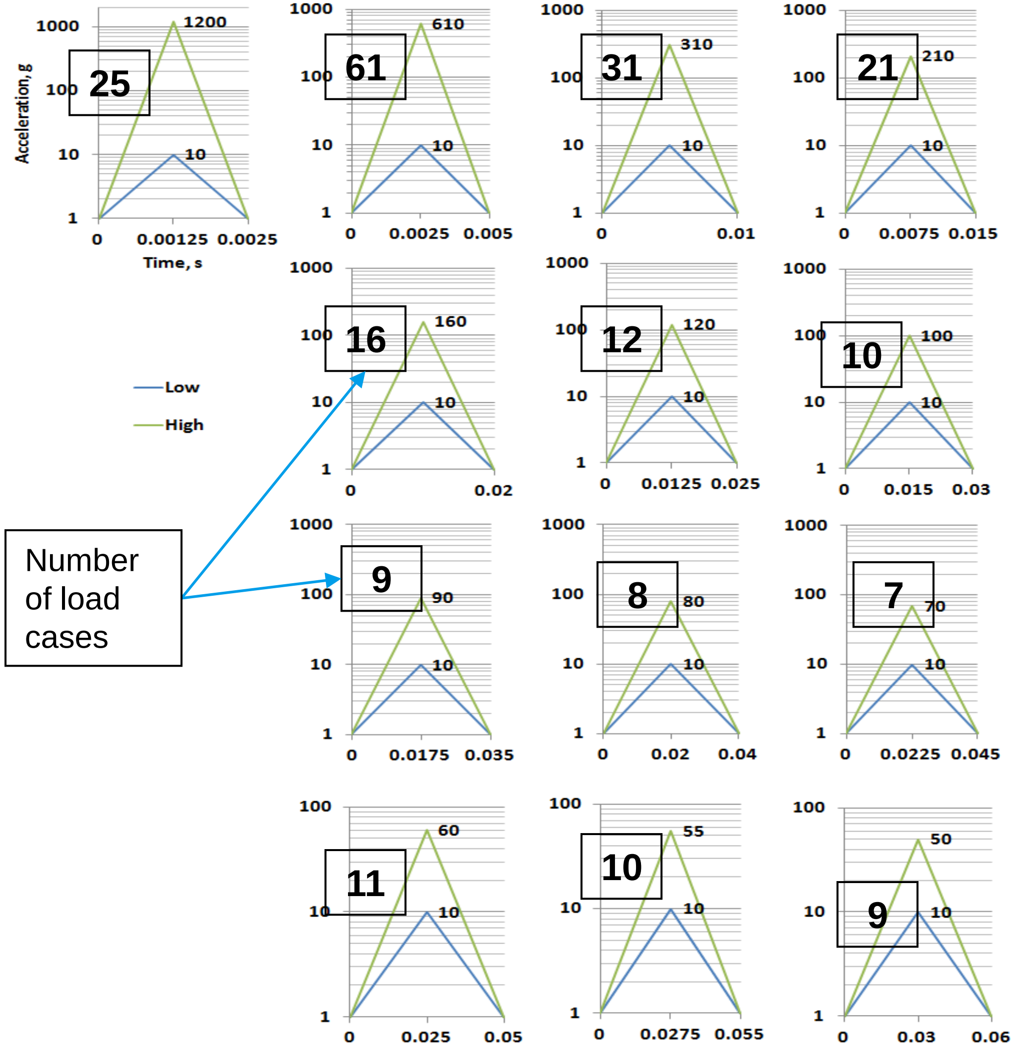
LSDYNA model with FTSS v7.1.6 finite element dummy



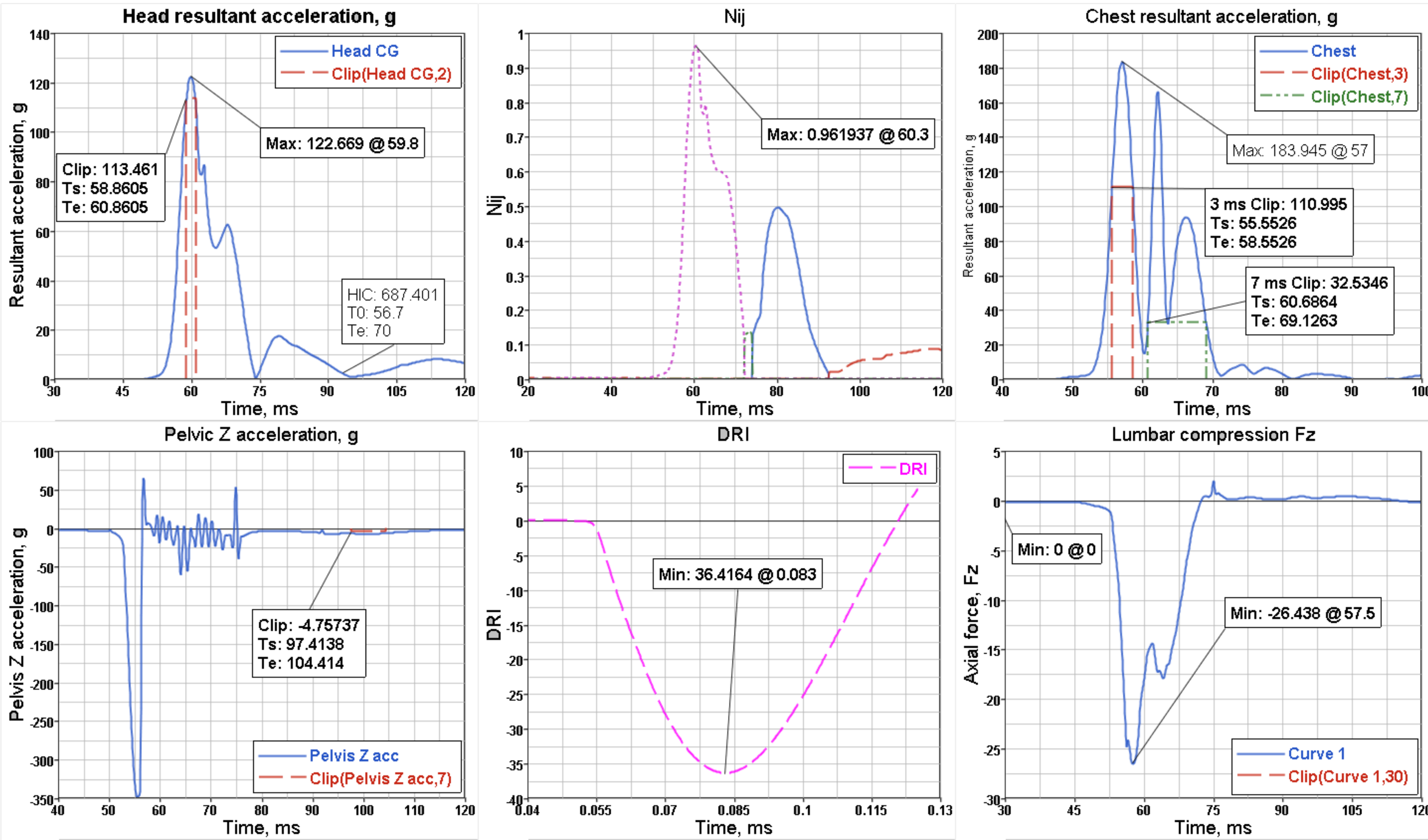

The two different EA systems (ideal) considered

# Parametric study

1. A triangular blast wave pulse was applied to the vertical drop tower sled.
2. A total of thirteen duration levels are studied; from 2.5 ms  to 60 ms.
3. At each of these duration levels, peak deceleration was varied from 10g with 10g increments up to the point when $\Delta v$ reached ~15m/s
4. A total of 230 runs were made each type of seat characteristic studied.
5. Three types of seat systems are; (i) Rigid (ii) Seat with a baseline EA (8kN) and (iii) A seat with softer EA (4kN)



# Recording injury metrics




Response from the dummy especially pelvic acceleration and spine compression was quite noisy and did not sustain continuously long enough for those input pulses with higher onset rates.

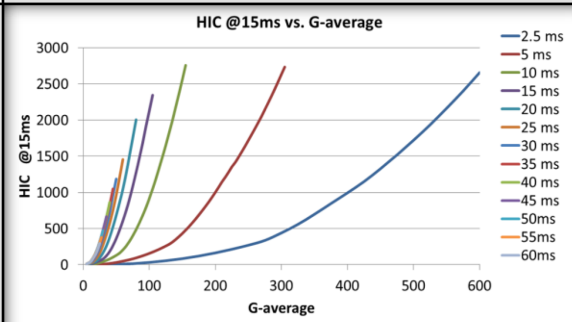
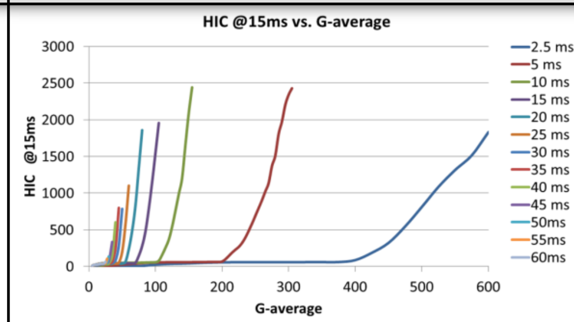
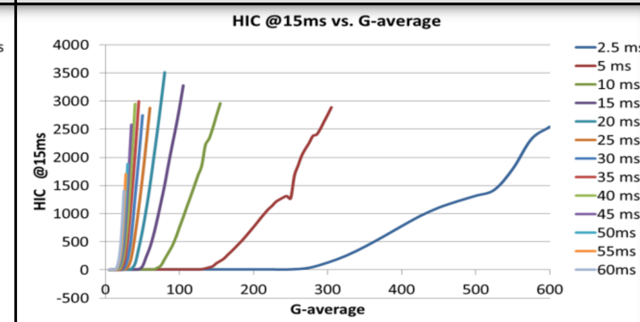
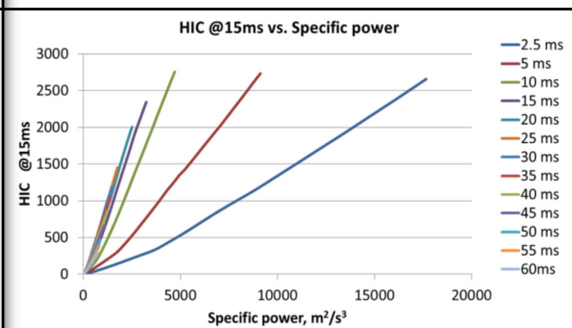
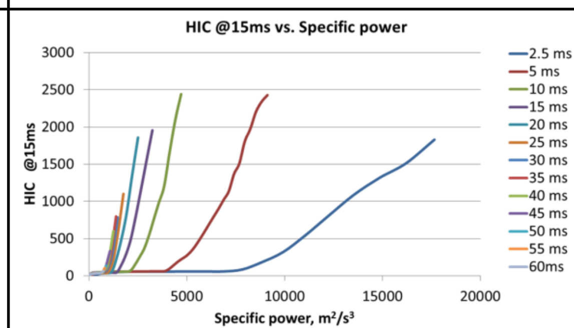
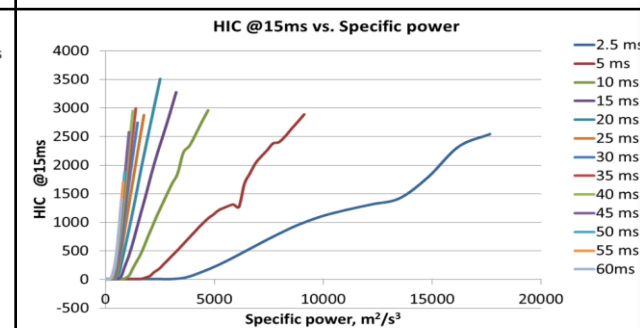
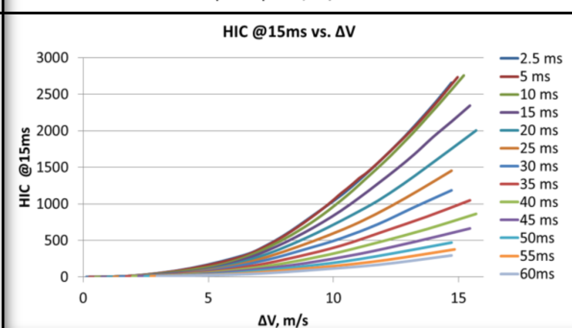
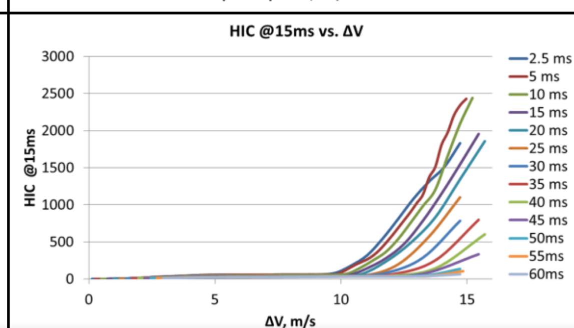
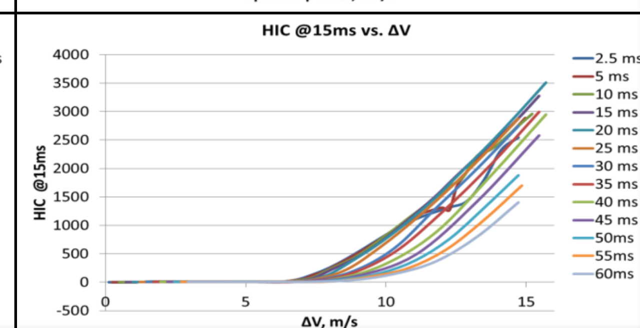
# Occupant injury responses

- **Three blast loading descriptors proposed in the literature, viz., $\Delta v$, $G_{eff}$, and Specific Power (*SP*) were evaluated for this purpose.**

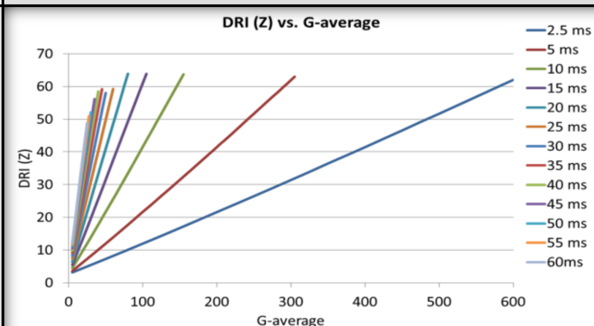
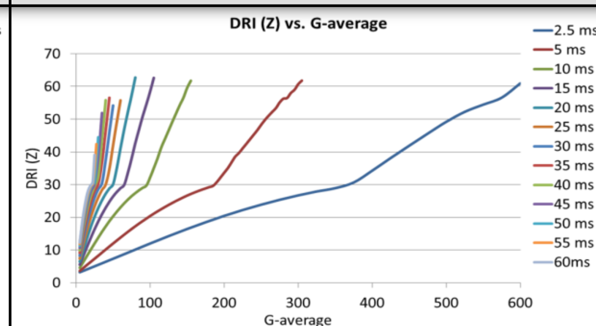
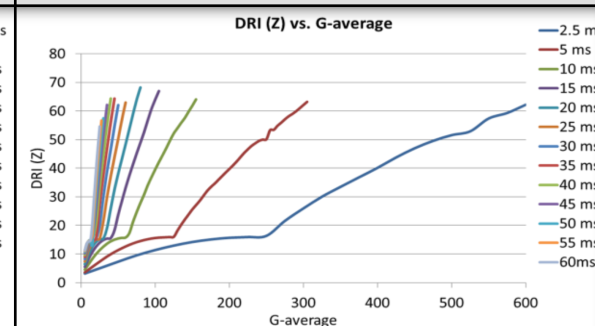
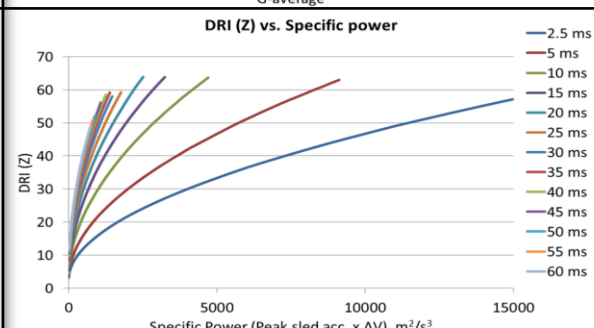
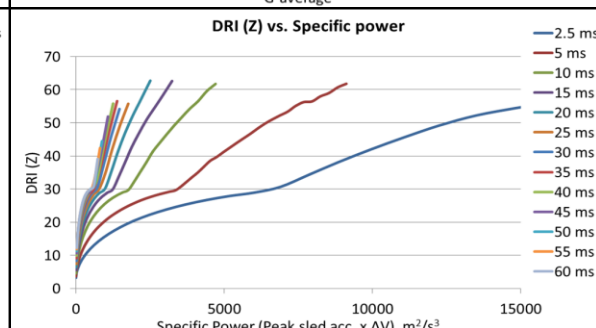
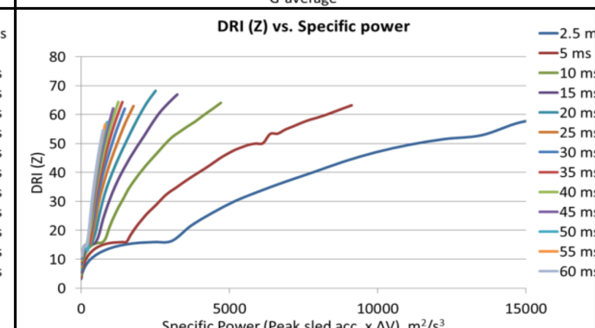
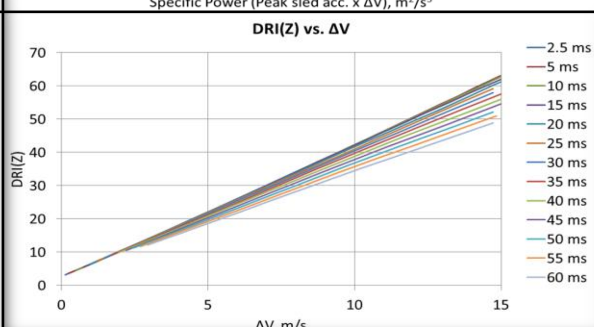
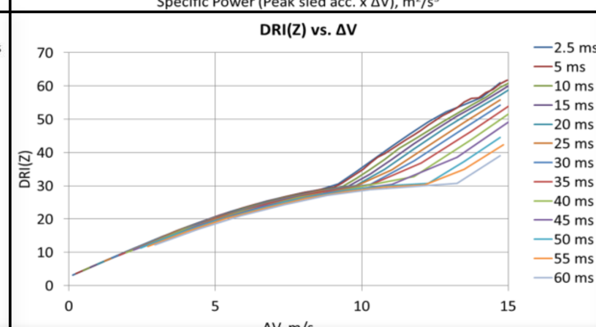
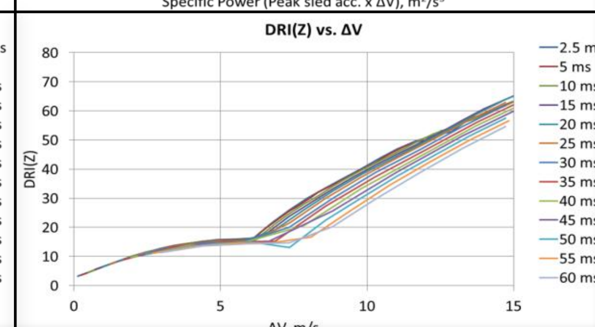
- **The ten occupant injuries considered in this study, are plotted against these blast loading descriptors, for the three seat types.**

- **A detailed regression study was conducted to see if there was a single blast loading parameter which could be used to adequately characterize occupant injuries.**

# Head Injury Criteria ($HIC_{15}$)

| | Rigid Seat | Seat w/ baseline EA | Seat w/ softer EA |
|---|---|---|---|
| Effective-g |  |  |  |
| Specific power |  |  |  |
| ΔV |  |  |  |

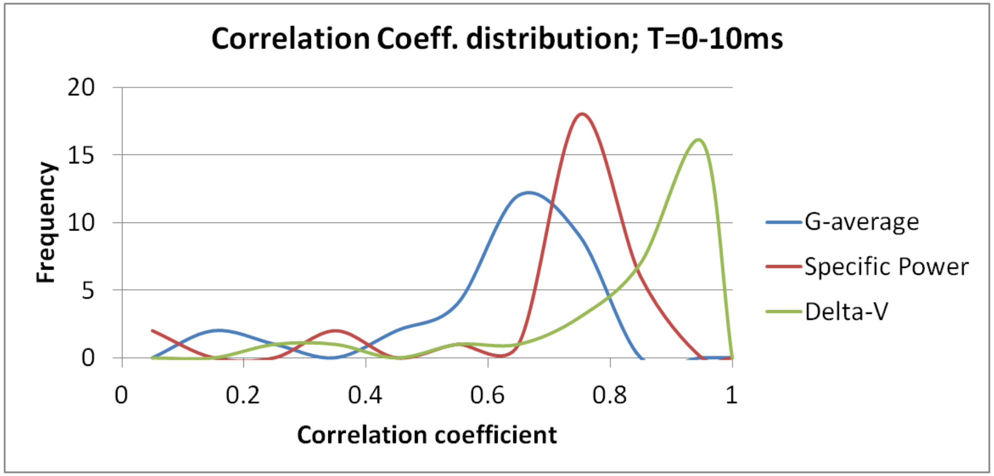
# DRI

| | Rigid Seat | Seat w/ baseline EA | Seat w/ softer EA |
|---|---|---|---|
| Effective-g |  |  |  |
| Specific power |  |  |  |
| ΔV |  |  |  |

# Correlation coeff. between Occupant Injury vs. Blast loading parameters

| | | Correlation Coefficients T from 0-10ms | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | G-average | | | Specific power | | | ΔV | | |
| | | Rigid | EA1 | EA2 | Rigid | EA1 | EA2 | Rigid | EA1 | EA2 |
| 1 | HIC @15ms | 0.67 | 0.52 | 0.59 | 0.81 | 0.74 | 0.74 | 0.94 | 0.74 | 0.89 |
| 2 | Head resultant acceleration @2ms | 0.73 | 0.63 | 0.65 | 0.79 | 0.77 | 0.77 | 1.00 | 0.85 | 0.96 |
| 3 | Head resultant acclelaration @0ms | 0.73 | 0.62 | 0.66 | 0.78 | 0.78 | 0.78 | 1.00 | 0.85 | 0.96 |
| 4 | Neck injury criteria, $N_{ij}$ | 0.71 | 0.61 | 0.65 | 0.79 | 0.77 | 0.77 | 1.00 | 0.84 | 0.95 |
| 5 | Chest resultant acceleration @3ms | 0.74 | 0.63 | 0.62 | 0.78 | 0.74 | 0.74 | 0.99 | 0.87 | 0.94 |
| 6 | Chest resultant acceleration @7ms | 0.65 | 0.57 | 0.73 | 0.72 | 0.80 | 0.80 | 0.96 | 0.83 | 0.95 |
| 7 | Lumbar spine compression @30ms | 0.59 | -0.42 | 0.19 | 0.53 | 0.40 | 0.40 | 0.77 | -0.65 | 0.30 |
| 8 | Lumbar spine compression @0ms | -0.75 | -0.66 | -0.68 | -0.80 | -0.81 | -0.81 | -1.00 | -0.88 | -0.96 |
| 9 | Pelvis vertical acceleration @7ms | -0.46 | -0.23 | -0.13 | -0.63 | -0.08 | -0.08 | -0.74 | -0.58 | -0.22 |
| 10 | DRI (Z) | 0.71 | 0.71 | 0.70 | 0.78 | 0.80 | 0.80 | 1.00 | 0.99 | 0.99 |

| | |
|---|---|
| (pink) | 0.5 < r < 0.75 |
| (yellow) | 0.75 < r < 0.9 |
| (green) | r > 0.9 |



# Preferred blast loading descriptor

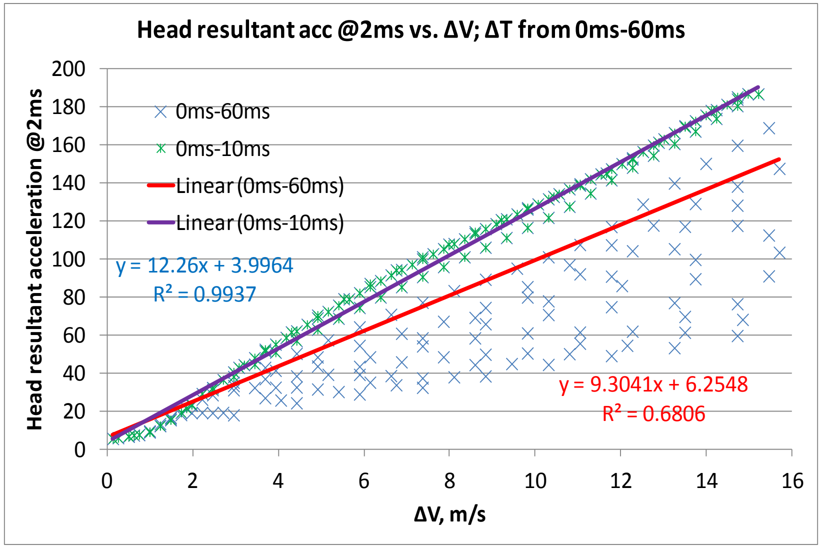
- None of the primary input pulse parameters considered in this study, by itself, is an indicator of occupant injury.
- One reason could be that our range of time duration of input pulses which ranged from 2.5 ms to 60 ms is too broad.
- Among the three loading parameters under consideration, $\Delta$***v* by itself**, has the potential to be a single good indicator in the typical blast loading range of 0-20ms.
- For a wider range of *T*, any of these primary parameters in combination with the pulse duration can be used to estimate occupant injury.

Using $\Delta$v as the blast loading descriptor three different approaches are considered in developing reduced order models.

# Reduced order models – Approach #1 (Single parameter)

Using the linear/quadratic regression equations resulting from this parametric study, occupant injuries for any triangular-shaped pulse can be easily computed.

e.g., Head acceleration (2ms clip) now can simply be calculated by using the linear regression equations from the curve above. For the entire range of *T*, i.e., 0 ≤ *T* ≤ 60ms,
**Head Acc (2ms clip) = 9.3041 * Δv + 6.2548**




- Similar regression equations can be constructed for other injuries and seat designs.
- One limitation of this approach is that if a single simple relationship for the entire range of pulses and durations of interest considered in this study were to be constructed, it would result in significant error.
- To minimize this error, for those pulses in the *typical blast loading range* i.e., 0 ≤ *T* ≤ 10ms, another set of regression equations can be derived; e.g., 0 ≤ *T* ≤ 10ms; **Head Acc (2ms clip) = 12.26 * Δv + 3.9964**

## Reduced order models – Approach #2 (Iso-T regression lines)

- This is an extension to the previous approach where regression analyses for the entire range of pulse durations, by suitably grouping them in to a finer (5ms in this study) intervals, is performed.
- This approach results in a set of regression lines for each group of pulse durations and therefore results in improved accuracy. For example, Head acceleration (2ms clip) regression equations are:

Head Acc. (2ms clip) = 12.368 * $\Delta$v + 4.7557 ($0 \leq T \leq 5$ms)

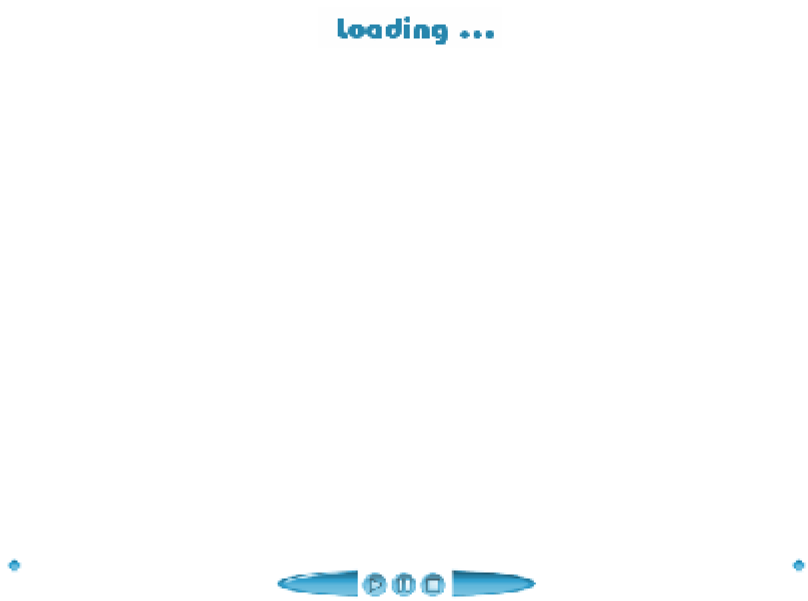
Head Acc. (2ms clip) = 12.03 * $\Delta$v + 1.3809 ($5 \leq T \leq 10$ms)

- 
- 
- 

Head Acc. (2ms clip) = 3.469 * $\Delta$v + 8.2534 ($55 \leq T \leq 60$ms)

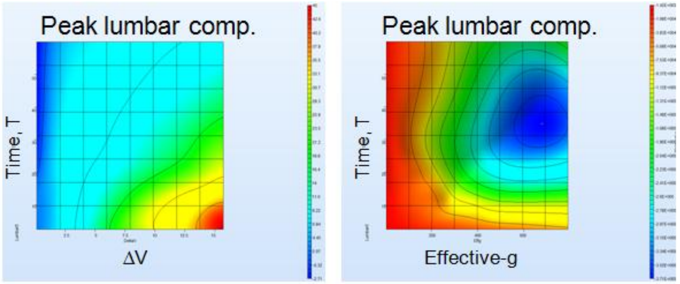
- Similarly linear regression equations can be derived for other occupant injuries.

# Injury lookup tool

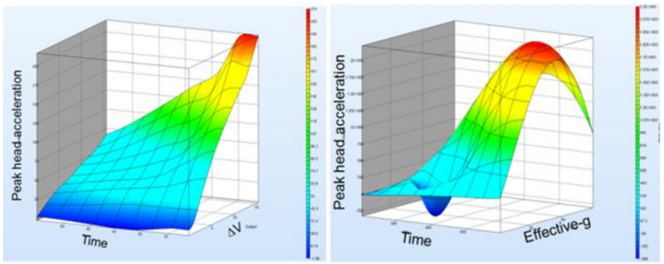


# Reduced order models – Approach #3 (Response surface metamodel)

Using the injury data obtained from the parametric M&S study, a surface-based metamodel was constructed using LSOPT®. Three-dimensional injury response surfaces were obtained for the ten injury parameters considered in this study from the LSOPT® simulations. Each of the injury surfaces was created as a function of the blast loading descriptor/s and the loading duration *T*.




Peak lumbar compression vs. Δv and Eff-g




Peak head acceleration vs. Δv and Eff-g

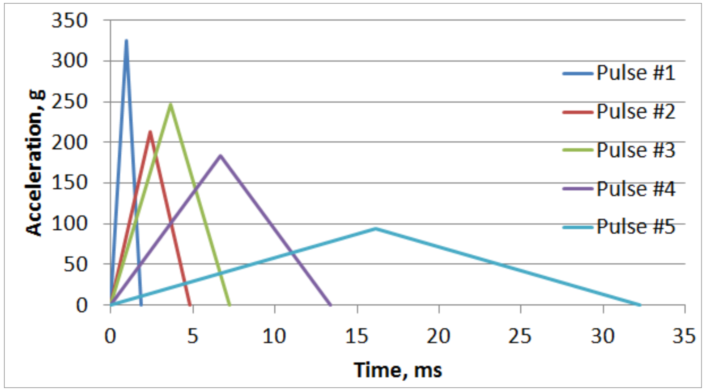
- One important observation that may be made is that both surfaces are mathematically equivalent.
- The uniformity of the surface against Δ*v* makes it a more suitable candidate for reduced errors during the numerical interpolations required for injury predictions using the response surface.

# Effectiveness of the injury lookup tool

- To demonstrate the accuracy and efficiency of using injury look-up tables five arbitrary pulses as shown in Figure and Table were selected, *which were not in the original seed simulations,* of the parametric M&S study.

- It can be seen that these arbitrarily chosen pulses do cover a wide range of $\Delta$v (3 -15 m/s) and T (2 – 32 ms).

- Occupant injuries as predicted by the three different approaches are compared against corresponding results from the direct MADYMO® simulations.




| Pulse # | Peak, Dec., g | Duration, ms | ΔV, m/s | Eff-g | Sp. Power |
|---|---|---|---|---|---|
| 1 | 324.43 | 1.85 | 2.94 | 213.51 | 955.11 |
| 2 | 212.40 | 4.80 | 5.00 | 139.78 | 1062.15 |
| 3 | 246.90 | 7.23 | 8.76 | 162.48 | 2161.82 |
| 4 | 183.63 | 13.40 | 12.07 | 120.85 | 2216.31 |
| 5 | 94.32 | 32.23 | 14.91 | 62.07 | 1406.39 |

# Prediction error from the three different approaches

**Approach #1**

| Occupant Injury | Pulse #1 | Pulse #2 | Pulse #3 | Pulse #4 | Pulse #5 |
|---|---|---|---|---|---|
| Head resultant acceleration 2ms-clip, g | -18% | -25% | -23% | -7% | 27% |
| Peak Head resultant acceleration, g | -17% | -26% | -24% | -10% | 26% |
| HIC 15 | -74% | -14% | 3% | 15% | 144% |
| Nij | -11% | -17% | -14% | -8% | 19% |
| Chest resultant acceleration, 3ms clip, g | 0% | -14% | -10% | 10% | 51% |
| DRI | -1% | -2% | -3% | -4% | 2% |
| Peak Lumbar Compression, kN | -11% | -24% | -27% | -12% | 50% |

**Approach #2**

| Occupant Injury | Pulse #1 | Pulse #2 | Pulse #3 | Pulse #4 | Pulse #5 |
|---|---|---|---|---|---|
| Head resultant acceleration 2ms-clip, g | 1% | -6% | 0% | -1% | 0% |
| Peak Head resultant acceleration, g | 4% | -7% | -2% | -5% | 0% |
| HIC 15 | -74% | -10% | 5% | -6% | 11% |
| Nij | 0% | -3% | 3% | -2% | -2% |
| Chest resultant acceleration, 3ms clip, g | 7% | -2% | 3% | -5% | 3% |
| DRI | 1% | 0% | 0% | -1% | 2% |
| Peak Lumbar Compression, kN | 7% | -3% | -1% | -7% | 4% |

**Approach #3**

| Occupant Injury | Pulse #1 | Pulse #2 | Pulse #3 | Pulse #4 | Pulse #5 |
|---|---|---|---|---|---|
| Head resultant acceleration 2ms-clip, g | 0% | 0% | -3% | 0% | 0% |
| Peak Head resultant acceleration, g | 1% | 0% | -1% | 0% | 0% |
| HIC 15 | 3% | 0% | -1% | 1% | 0% |
| Nij | 0% | 0% | 0% | 0% | 0% |
| Chest resultant acceleration, 3ms clip, g | 0% | 0% | -1% | 0% | 0% |
| DRI | 0% | 0% | 0% | 0% | 0% |
| Peak Lumbar Compression, kN | -1% | 0% | -2% | -1% | 1% |

# Conclusions

1. Three different reduced order modeling approaches of increasing fidelity and accuracy were constructed and evaluated for their ability to predict occupant injury behavior.

2. An easy-to-use, rapid injury estimator tool was constructed in Microsoft Excel® as a function of input load descriptors, using the occupant injury regression trends obtained from a detailed parametric study.

3. This tool takes mere seconds to arrive at accurate injury predictions when compared to the direct method which takes a minimum 20 minutes with additional time required for post-processing, plotting, and tabulation, etc. by an expert user. Also this tool does not require the expensive software, training and hardware associated with the direct method.

4. This tool will enable decision makers to quickly arrive at informed decisions during early concept design stages, Analysis of Alternatives (AoA) studies, etc

# Conclusions

5. It is noteworthy that these results are only representative of the underlying power of the technology. By extending this methodology to one or more seats with the EA as one of the design variables, family of better validated ATDs of different sizes, new and improved injury criteria from the bio-medical research the tool can be made extremely useful in ground vehicle acquisition.

6. The methodology used in this project is being planned for extended use elsewhere in the Army for data from physical drop tower/vertical sled tests, as well as from Live-Fire blast tests to develop similar empirically-based tools for use by designers, program managers, evaluators, etc.

7. This methodology can also be used elsewhere in the automotive industry to develop reduced order models using occupant injury tables to assist conceptual studies during early phase of product development.

# Disclaimer

Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Dept. of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoD, and shall not be used for advertising or product endorsement purposes.

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